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Director of Research

COREC - EXPERT SYSTEM FOR RECOGNITION AND IDENTIFICATION OF FORMS OF CORROSION ATTACK

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COREC expert system package was developed for use by engineers, who are not corrosion specialists, but are required to solve corrosion problems as a part of their work duties. It is intended to assist their efforts to recognize and identify a form of corrosion attack during investigation into equipment and structural failures. The program guides the user to the most likely form of corrosion attack by asking simple questions, answers to which can be obtained by determining the type of service environment in which the component failed and by visual inspection of the component appearance characteristics.

Correct recognition of a corrosion form is essential for diagnosis of the failure mechanism and solution of the problem. Proper corrective and preventive measurers can be taken if the form of corrosion attack is known with certainty. With the assistance of this expert system, 16 basic corrosion mechanisms, which can independently or jointly bring a component to failure can be recognized.

The COREC expert system package is designed for ease of use, and no previous computer experience or computer programming knowledge is required.

1.0 INTRODUCTION

Billions of dollars each year can be saved by better utilization of available information on corrosion prevention and control technology, materials performance, and suppliers of equipment and materials. In order to apply this knowledge, it is necessary to correctly recognize and identify the form of corrosion attack that causes failure. This expert system was developed to aid engineers, who are not corrosion specialists, with the first stage of corrosion problem diagnosis by correctly recognizing the form of corrosion attack.

Determination of the form of corrosion attack is important for the prevention of future problems. The root cause for a failure can be established and proper ameliorative measures taken only when the failure mechanism is identified correctly. The correct identification of failure mechanism is a complex process which may include many individuals and institutions. Technical specialists in metallurgy, chemistry and mechanical engineering frequently cooperate in a failure investigation. These individuals rely on personal

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experience and a tremendous amount of reports, theories, studies, private communications and investigations concerning the different failure modes and mechanisms.

As a result of many years of serious effort by the corrosion scientists and engineers to mitigate the problem of corrosion attack, information exists that makes possible correct identification of all routine forms of corrosion which are currently known. It is believed that proper dissemination of this knowledge and future findings will contribute to fewer incidents of failures. Expert systems, also known as knowledge based systems, appear to be effective tools for transferring this knowledge gained through research and field experience to individuals responsible for the design, construction, operation and maintenance of equipment and structures. Expert systems are generally considered to be computer programs that use knowledge and inference procedures to solve problems instead of the traditional programs utilizing data and algorithms.

This report describes an expert system called COREC, which has been developed to aid in correct identification of corrosion forms. The purpose of this expert system is to provide support to the staff charged with the responsibility of determining the root cause or causes of the failures and the implementation of proper corrective measures.

2.0 WHY EXPERT SYSTEMS?

An expert system like the one described here offers the following benefits:

- The knowledge about a limited domain is captured in the detail required for machine logic processing; a good knowledge representation will identify areas where the knowledge is uncertain or incomplete; areas for further work become clearly defined and the programs to be carried out are readily apparent (sharpening the expert).

- Human experts can be distracted or rushed and led to incorrect or inconsistent deductions; the expert system will always apply the same logic and give consistent results; the results will be correct if the rules are; when the expert system cannot arrive at a conclusion it refers the user to a human expert (best knowledge base always gives best conclusions).

- All conclusions reached by the expert system are justified by inspectable rules; the human expert is freed from remembering all the details of the justification; this is a great time saver in areas where justification is repeatedly requested for slightly different inputs; in cases of disagreement among experts, the knowledge base challenges other experts to point out errors or to generate a correct rule base (public thinking tool).

- With appropriate help facilities, an expert system can become an excellent tutor for transferring knowledge from an expert to his successor; this provides a company with some measure of protection against loss of expertise through attrition (preservation of knowledge).

- Non-specialists have access to expert knowledge if the expert is not available; problems that are well understood can be solved by anyone who has access to the expert system, this frees the expert from repeatedly executing the same tasks so that he can concentrate his efforts on acquiring new knowledge (efficient use of manpower).

The risks involved in the use of expert systems are the same as those associated with any computer program. The conclusions arrived at by an expert system may be wrong if the rules are incorrectly written and/or when the data entered by the user are wrong. Although the COREC is designed to guard against misinterpretation, conclusions should be treated like any conclusions of a single expert. A second opinion is recommended if an incorrect conclusion entails great risks.

3.0 SOURCE OF KNOWLEDGE

The acceptance of an expert system depends on the credibility of its knowledge base. In the conceptual design of the COREC, two criteria were established for selecting the main source for the factual portion of the knowledge base. The facts should have been: (1) published in public domain so that their reliability could be judged; and (2) accepted by the practising experts in the area of corrosion failure analysis.

The books by Fontana and Green/1/, Uhlig/2/, Evans/3/, Pludek/4/ and ASM Handbook/5/ met both criteria and were chosen to provide the factual framework for the COREC.

The COREC knowledge base was constructed around 16 basic forms of corrosion, which can independently or jointly cause failure. The form of corrosion can be determined, with a high degree of certainty, from the type of service environment and characteristic appearance parameters. The relationships between forms of corrosion attack and these factors are well established.

This knowledge is organized into a decision tree structure incorporating the facts from the corrosion engineering and scientific literature and heuristic components contributed by the developer of the COREC. The facts are expressed in the form of production rules using an expert system development package called EXSYS.

4.0 COREC - EXPERT SYSTEM PACKAGE

COREC expert system package was developed for use by engineers, who are not corrosion specialists, but are required to solve corrosion problems as a part of their duties. It is intended to assist their efforts to recognize and identify a form of corrosion attack during investigation into equipment and structural failures. The program guides the user to the most likely form of corrosion attack by asking simple questions, answers to which can be obtained by determining the type of service environment in which the component failed and by visual inspection of the component appearance characteristics.

Use of this expert system package does not eliminate the need for a thorough metallurgical analysis during the failure investigation since such an analysis is essential in many cases to confirm or ascertain the responsible failure mechanism.

4.1 Expert System Development Package

EXSYS/6/ is a generalized expert system development package. Expert system is a type of artificial intelligence program that emulates the interaction a user might have with a human expert on a subject area. Expert systems developed with EXSYS asks the user questions relevant to a subject. The user answers by selecting one or more answers from a list by entering a numeric value. The computer will continue to ask questions until it has reached a conclusion. The conclusion may be the selection of a single solution or a list of possible solutions arranged in order of likelihood. The computer can explain, in English, how it arrived at its conclusion and why.

Expert systems can be developed for any problem that involves selection from among a definable group of choices where the decision is based on logical rules. The rules can involve relative probabilities of a choice being correct. Any area where there is a person or group of persons that have special expertise needed by others is a possible area for expert systems. Anything from identification of biological specimens, to automating complex regulations, to aiding customers in selecting from among a group of products, to automated user assistance is possible.

Expert systems deal with knowledge rather than data and the files they use are often referred to as

Expert systems deal with knowledge rather than data and the files they use are often referred to as knowledge bases. The rules that the program uses are IF-THEN type rules. A rule is made up of a list of IF conditions (normal English sentences) and a list of THEN conditions (more sentences) or statements about the probability of a particular choice being the appropriate solution to the problem. If the computer determines that all of the IF conditions in a rule are true it adds the rule's THEN conditions to what it knows to be true. The computer determines what additional information it needs and how best to get this information. If possible, the program will derive information from other rules rather than asking the user. This ability to derive information allows the program to combine many small pieces of knowledge to arrive at logical conclusions about complex problems.

The final goal of an expert system is to select the most appropriate solution to a problem based on the data input by the user.

4.2 Knowledge Organization and Utilization

Over the years, corrosion scientists and engineers have recognized that corrosion manifests itself in forms that have certain similarities and therefore can be categorized into specific groups. However, many of these forms are not unique but involve mechanisms that have overlapping characteristics that may influence or control initiation or propagation of a specific type of corrosion.

The most familiar and often used categorization of corrosion is probably the eight forms presented by Fontana and Greene/1/: uniform attack, crevice corrosion, pitting, intergranular corrosion, selective leaching, erosion corrosion, stress corrosion, and hydrogen damage. This classification of corrosion was based on visual characteristics of the morphology of attack. Fontana and Greene's introductory remarks in their chapter on forms of corrosion indicate that this classification is arbitrary and that many of the forms are interrelated, making exact distinction impossible. Other prominent corrosion authors such as Uhlig/2/ and Evans/3/ have avoided a classification format and have simply discussed the classical types of corrosion (for example, pitting and crevice corrosion) as they relate to specific metals and alloys.

Substantial advances in the field of corrosion science have begun to define the mechanisms of many forms of corrosion more clearly. However, rather than placing the mechanisms into distinct categories, the overlap between many of the forms has become greater. For example, there is evidence that hydrogen may dominate the crack initiation or crack propagation portion of fracture in some metal/solution systems where stress-corrosion cracking occurs. Additionally, in some metal systems where dealloying (selective leaching) occurs, this form of corrosion may be a precursor to stress-corrosion cracking.

In a similar vein, the magnitude of contribution of stress or corrosion to stress-corrosion cracking, hydrogen damage, or liquid metal embrittelment is not currently understood and can affect whether just pitting or crevice attack occurs or environmental cracking results. The transition from uniform corrosion to highly localized attack is not clearly understood, and there are conditions where a distinction cannot be drawn.

The forms of corrosion presented in the ASM Metals Handbook/5/ were categorized to represent the mechanisms of attack involved rather than to emphasize the visual characteristics. However, as with any classification system, these categories are not distinct or all-inclusive and do not necessarily represent the only mode of attack that may be observed. The forms of corrosion are categorized as:

- General Corrosion
  - Atmospheric corrosion
  - Galvanic corrosion
  - Stray-current corrosion
  - General biological corrosion
  - Molten salt corrosion

- Corrosion in liquid metals

- High-temperature corrosion
  - Oxidation
  - Sulfidation
  - Carbunization
  - Hydrogen effects
  - Hot Corrosion

- Localized Corrosion
  - Filiform corrosion
  - Crevice corrosion
  - Pitting corrosion
  - Localized biological corrosion

- Metallurgically Influenced Corrosion
  - Intergranular corrosion
  - Dealloying corrosion

- Mechanically Assisted Degradation
  - Erosion corrosion
  - Fretting corrosion
  - Cavitation and water drop impingement
  - Corrosion fatigue

- Environmentally Induced Cracking
  - Stress-corrosion cracking
  - Hydrogen damage
  - Liquid metal embrittlement
  - Solid metal induced embrittlement

As a result of the arbitrary nature of classifying forms of corrosion and the fact that corrosion science is a dynamic field with ever-changing theories and observations, the distinctions between many forms become highly personalized. Other articles contain variations of these forms of corrosion. This does not imply a misunderstanding of the mechanisms of corrosion, but rather underscores the continuing evolution of corrosion theory.

The COREC expert system is based on a classification variation which was viewed to be more useful for practising corrosion engineers than classifications based on purely visual characteristics or mechanism of attack. The forms of corrosion considered in COREC are:

- Cavitation Damage
- Concentration Cell Corrosion
- Crevice Corrosion
- Erosion - Corrosion (Dry)
- Erosion - Corrosion (Wet)
- Erosion - Corrosion (Impingement)
- Fatigue Corrosion
- Fretting Corrosion
- Galvanic Corrosion
- High Temperature Corrosion
- Hydrogen Damage

- interganular Corrosion
- Pitting Corrosion
- Selective Attack (Leaching)
- Stray Current Corrosion - (Electrolysis)
- Stress Corrosion Cracking
- Thermogalvanic Corrosion
- Uniform (General) Corrosion.

To diagnose these forms of corrosion, the user must be able to determine the following factors: recognize visually different types of metal loss and/or damage, establish environmental conditions, potential causes of corrosion attack and several mechanical factors which can enhance corrosion.

There are two principal types of corrosion attack: metal loss and stress cracking in presence of a corrosive. The metal loss can be:

- uniform
- localized
- intergranular
- extraction of soluble phase

The environments which usually cause corrosion are:

- Gases and vapours
  - Flue gases
    - Reducing
    - Oxidising
  - Chemical fumes
  - Steam
    - Wet
    - Dry
  - Atmospheric
    - Contamination (H_2S, $S0_2$, $S0_3$, NH_3, HCl, NH_4Cl, etc. Solids.)
    - Nitrogen and Carbon dioxide
    - Oxygen
      - Wet
      - Dry
    - Atmosphere
      - Wet
      - Dry

- Liquids
  - Aqueous or "wet"
    - Natural
      - Sea water
      - River and estuarine waters
      - Potable waters
      - Underground
      - Biochemical
    - Chemicals
      - Acid
      - Neutral
      - Alkaline

        - Complex Reforming
    - Foodstuffs
- Non-aqueous
    - Fused salts
    - Liquid metal
    - Organic liquids and solutions

Additional environmental factors which influence the form of corrosion attack are:

- aggressivity of liquid
- aggressivity of gas
- temperature.

The potential causes of corrosion attack are:

- dissimilar metal in contract
- differences in concentration of dissolved gases or ions in liquids
- crevices
- heat affected zone adjacent to weld
- defective coating
- insulation
- deposits
- stray current.

The mechanical factors which may enhance the corrosion attack are:

- constant applied or residual stress
- alternating stress
- moving contract with other component
- moving corrosive with or without abrasive particles.

The COREC guides the user to the correct form of corrosion, characterized by the observed factors, utilizing a structured multiple-choice inquiry. The program requests information only on unique factors which are needed to unequivocally define the form of corrosion of the component under investigation.

5.0 EXAMPLE OF A DIAGNOSTIC SESSION

For the purpose of demonstrating a diagnostic session with the COREC expert system, a failed component from a coal fired electric power generating station was chosen for analysis. This component was a tube/7/ from a low pressure boiler feedwater heater (FWH) after about 20,000 hours of operation.

5.1 Failed Component and System Description

Initial inspection of the failed tube indicated that the tube wall penetration, located at the bend, was caused by a metal wastage process initiated from the tube bore exposed to feedwater. Damage was also noted at the outlet end where significant wall thinning occurred.

5.1.1 Equipment, Operating Conditions and Feedwater Heater Description

A simplified power plant water/system loop is shown in Figure 1.

The fourth point FWH is the last heat exchanger of low pressure heaters before the feedwater enters the deaerator. The FWH tubes are exposed to feedwater on the bore side and steam and condensate on the shell side. A schematic cross-section of the horizontal FWH (Figure 2), illustrates the design features and main components.

The relevant design data and operating conditions are summarized in Table 1.

The tubes are made of Admiralty Brass (SB-1111 C443), a 70/30 Cu/Zn alloy with up to 0.1% As. The U-tubes had been stress-relieved for one hour at 288C° after bending. The feedwater is supplied to a natural circulation drum boiler of 19 MPa design pressure.

5.1.2 Feedwater Chemistry

The feedwater pH control system was designed to maintain the pH at about 8.8 by injecting morpholine at the condensate extraction pump discharge between the gland steam condenser and the drains coolers (see Figure 1). The pH measured at the deaerator is used to control the amine pump stroke (0 to 100%), varying the injection rate from 0 to 28 L/hr.

The average concentration of morpholine at the point of injection is 110 ppb at full condensate flow. During a unit start up when amine pump stroke is at a minimum, the morpholine concentration in the condensate at the point of injection can theoretically exceed 1,500 ppb.

Hydrazine is added at the deaerator outlet to assist in oxygen removal.

5.1.3 Visual Investigation - Internal Surface Damage Location and Appearance

Visual and low power stereo microscopic examination of the internal surface indicated that most of the internal surface was covered with a loosely adherent reddish brown deposit. Underneath this deposit, an indigenous black adherent oxide was found adjacent to the metal surface. At certain locations, confined mainly to the bend, the surface was covered with a light grey thin oxide only; no deposited materials were identified at this location.

In the grey oxide area elongated pits having a horseshoe-like shape, reminiscent of a horse walking up a stream, were observed (Figure 3), giving the surface a scalloped appearance.

The shape of the pits reveals information related to the direction of water flow: the open end points are typically at the downstream location of the flow direction. The information reported in literature on erosion/corrosion of steels associates initiation of this type of attack with a breakdown in the protective oxide found on the internal surface of the tubes. When this localized breakdown of the protective film occurs, galvanic effects enhance the corrosion and pits spread laterally. This spread is deflected around any stable point where isolated islands of scale or other similar protuberances exist, causing characteristic "horseshoe" shaped pits to develop.

5.2 Diagnosis of Corrosion Form

First, the COREC expert system displays an opening text:

SCREEN #1.

INTRODUCTION

COREC expert system package was developed for use by engineers, who are not corrosion specialists, but are required to solve corrosion problems as a part of their duties. It is intended to assist their efforts to recognize and identify form(s) of corrosion attack during investigation into equipment and/or structural failures. The program guides the user to the most likely form of corrosion attack by asking simple questions, answers to which can be obtained by determining the type of service environment in which the failure occurred and by visual inspection of the failed component appearance characteristics.

Correct recognition of the corrosion form is essential for diagnosis of the failure mechanism and solution of the problem. Proper corrective and preventive measures can be taken only if the form of corrosion attack is known.

Before use, please read the manual carefully. After that simply follow the directions on the screen.

Press any key to start:

Next the system requests information on the type of environment the tube was exposed to.

SCREEN #2

Component failure occurred in environment which is

1 corrosive liquid and/or gas
2 not corrosive liquid and/or gas

Enter number(s) of value(s), WHY for information on the rule, <?> for more details, QUIT to save data entered or <H> for help

The feedwater at elevated temperature is a potentially corrosive environment, therefore the user enters #1 and ENTER.

The system automatically determines what to ask next to determine the form of corrosion attack. In this case information on the type of metal damage is needed.

SCREEN #3.

Component failure is caused

1 by metal loss
2 by cracking without significant metal loss

Enter number(s) of value(s), WHY for information on the rule, <?> for more details,
QUIT to save data entered or <H> for help

The component failed by metal loss, therefore the user enters #1 and ENTER

Since corrosion by metal loss can occur due to various causes, the system is asking for further information.

SCREEN #4.

Metal loss is

1 uniform
2 localized
3 intergranular
4 by extraction of soluble phase

Enter number(s) of value(s), WHY for information on the rule, <?> for more details,
QUIT to save data entered or <H> for help.

The metal damage was localized and the horseshoe-like depressions gave the surface a scalloped appearance. Therefore the user enters #2 and ENTER.

SCREEN #5

Failed component was

1 in moving contact with other component(s)
2 not in moving contact with other component(s)

Enter number(s) of value(s), WHY for information on the rule, <?> for more details,
QUIT to save data entered or <H> for help.

The tube is not in moving contact with other components, the user enters #2 and ENTER.
Additional information is needed to determine the form of the localized corrosion attack under investigation.

SCREEN #6

At failure location was/were

1 two dissimilar metals in contact
2 crevice(s)
3 pit(s)
4 induced electrical current discharged to earth
5 temperature different from that at other parts of component
6 composition of the corrosive liquid different from that in contact with other parts of component
7 moving corrosive environment in contact with component

Enter number(s) of value(s), WHY for information on the rule, <?> for more details,
QUIT to save data entered or <H> for help.

At the failure location one elongated pits and the boiler feedwater flows in large quantities through the heater, therefore the user enters #3, #7 and ENTER.

The system must determine whether the corrosive rnedia is gas or liquid.

SCREEN #7

Corrosive environment was

1 dry
2 wet

Enter number(s) of value(s), WHY for information on the rule, <?> for mo e details,
QUIT to save data entered or <H> for help.

The feedwater is a wet corrosive environment, therefore the user enters #2 and ENTER.
The direction of corrosive liquid flow is the next information needed before final corrosion form determination.

SCREEN #8

Corrosive liquid flow was

1 parallel with component surface
2 perpendicular to component surface

Enter number(s) of value(s), WHY for information on the rule, <?> for more details,
QUIT to save data entered or <H> for help.

The most metal damage occurred where the feedwater flow changed direction at the tube bends. Therefore, the user enters #2 and ENTER.

Based on the provided information, the system performs diagnosis and determines the form of the corrosion attack under investigation and displays the conclusion on the screen with short description of the corrosion form.

SCREEN #9

The form of corrosion attack is "Erosion-Corrosion (Impingement)"

DEFINITION

Impingement attack is a localised corrosion resulting from the action of liquid on a surface. The effect is enhanced by erosion if the liquid is laden with solids.

CAUSE

Impingement attack is caused by a liquid which may be laden with solid particles breaking through corrosion scale and eroding the metal. The effect depends mainly on liquid velocity and amount of entrained solids, and any factor which affects the rate of protective scale formation.

PREVENTIVE MEASURES

Decrease liquid stream velocity to improve lamellar flow.
Regulate content of entrained air in liquid environment to suit the metal.
Reduce amount of entrained solid particles.
Streamline the flow; avoid design which creates turbulence or flow restriction.
Minimise abrupt changes in flow direction.
Align pipe sections.
Streamline inlets and outlets.
Avoid obstructions; real or potential
Increase thickness of material in vulnerable ares.
Install replaceable shields, plates or baffles.
Design for each removal and installation of replaceable components.
Provide filter for removal of abrasive contaminants.
Introduce smooth aerodynamic or hydrodynamic surfaces.
Avoid rough texture of surfaces.
Select suitable materials.
Specify suitable coatings and linings.
Protect cathodically.

Next the system gives the user an option to print the conclusions.

SCREEN #10

Please input YES if you would like the conclusions which were just displayed to be printed, or NO otherwise.

Input the text for the variable "WHY" for information, <?> for more details or "QUIT" to safe data:

The user types YES or NO.

The screen before final summary of the conclusions provides warning to the user and additional instructions:

SCREEN #11:

The following screen will display a summary of the conclusions. Pressing <P> will allow you to print this summary, as well as the data you provided as answers to the questions.

CAUTION:

Use of this Expert System Package dos not eliminate the need for a thorough metallurgical analysis during the failure investigation. All conclusions should be treated like any conclusions of a single expert. A second opinion is recommended if an incorrect conclusion entails great risks.

Press any key to display results.

If the user presses <P>, the following summary is printed.

SCREEN #12

1 Form of corrosion attack is EROSION - CORROSION (IMPINGEMENT)

Component failure occurred in environment which is corrosive liquid and/or gas
Component failure is caused by metal loss.

Metal loss is localized.

Failed component was not in moving contact with other component(s).

At failure location was/were moving corrosive environment in contact with component.

Corrosive environment was wet.

Corrosive liquid flow was perpendicular to component surface.

This ends the diagnosis session.

The user, if interested, can obtain background information on the diagnosed form of corrosion attack from the publications listed in Section 1.2 "Source of Knowledge".

6.0 SUMMARY

The COREC expert system package was developed for use by enineers, who are not corrosion specialists, but need to solve corrosion problems as a part of their work duties.

The factual knowledge base for this expert system is based on the best available information in the public domain and heuristic knowledge of the author of this report/1, 2, 3, 4, and 5/.

The program guides the user to the most likely form of corrosion attack by asking simple questions, answers to which can be obtained by determining the type of service environment in which the component failed and by visual inspection of the component appearance characteristics.

The potential user is advised to customize this generic expert system before use to incorporate into it "site specific" information, e.g., environments, materials and failure types.

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TABLE 1

FOURTH POINT LP HEATER DESIGN AND OPERATING CONDITIONS

Feedwater - flow rate (Kg/s)	346
Inlet temperature (°C)	116.3
Outlet temperature (°C)	144.8
Metal temperature at the bend (°C)	136.0
Design velocity in tubes at 16°C (m/s)	2.0
Design velocity in the tubes at 136°C (m/s)	2.1
Feedwater pH	8.8
Tubes	
- Number of passes	2
- Surface area (m^2)	828
- Number "U" bends	810
- OD x thickness (mm)	19.1 x 1.24
- Ave straight length (m)	17.1
- Material	SB-111-C443-Admiralty Brass

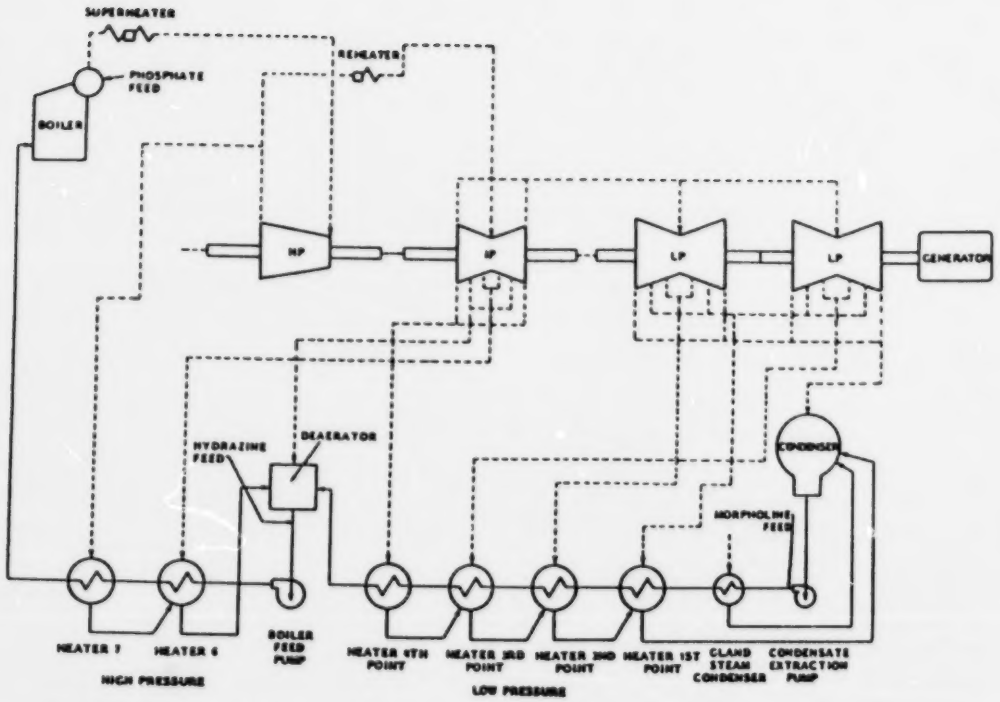

FIGURE 1: Condensate and Feedwater Flow Diagram showing FWH layout, sampling points, chemical injection points and operating temperatures.

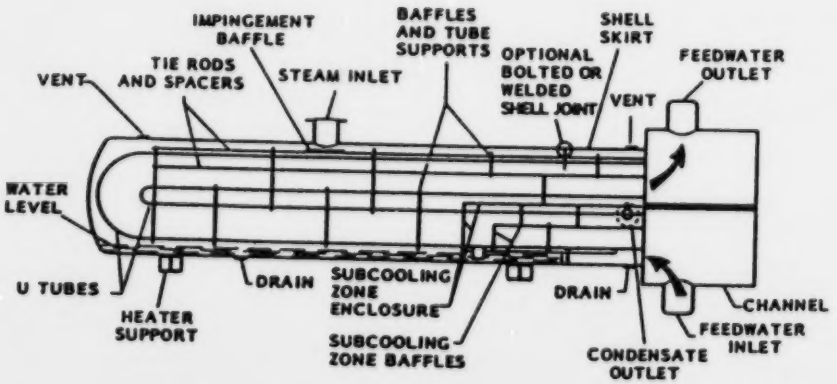

FIGURE 2: Schematic of the low pressure U-Tube closed feedwater heater.

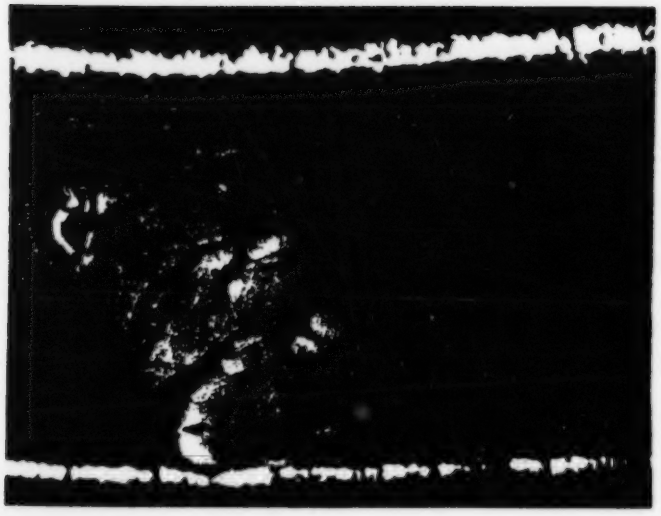

FIGURE 3: Typical condition of internal surface of the tube at the bend showing large and deep damage (Hoseshoe-like pits).